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FINAL REPORT ON THE COMPARATIVE COMBUSTION PROPERTIES OF RAW AND WASHED PRINCE MINE COAL

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FINAL REPORT ON THE COMPARATIVE COMBUSTION PROPERTIES OF RAW AND WASHED PRINCE MINE COAL

by

G.N. Banks*, J.K.L. Wong** and H. Whaley***

ABSTRACT

The combustion performance of raw Prince mine coal (run of mine) and five levels of cleaned (washed) Prince mine coal was compared with that of a commercially available thermal bituminous coal from Western Canada. Tests were conducted in a pilot-scale pulverized coal-fired research boiler located at the Energy Research Laboratories in Ottawa.

Two of the cleaned coal samples were obtained from the Electric Power Research Institute (EPRI) Homer City coal cleaning facility in the USA and the other three were obtained from the CANMET Coal Research Laboratories coal cleaning facility in Devon, Alberta. Chemical, physical, petrographic and thermogravimetric analyses were performed on samples of the coals. Each of the coals flowed readily through the Energy Research Laboratories pilot-scale conveying and coal-handling system.

The coals, which ground readily to produce a consistent size product from the pulverizer, all ignited easily to produce stable flames at greater than 96% combustion efficiency. The highest combustion efficiencies (>99%) were obtained with the more finely ground coal feeds. Although the two washed coals with the lowest ash content gave the higher combustion efficiencies, the raw coal, which had the lowest fly ash combustible content, also gave a combustion efficiency greater than 99%.

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The ash from each of the Prince mine coals was quite fluid and slagged readily in the refractory-lined furnace bottom, whereas the ash deposits on the water-walls and superheater surfaces were light and powdery and did not constitute a fouling problem.

The sulphur content of the coal was not significantly lowered until the ash content of the coal was reduced to less than 7%. A reduction to 2.4% ash resulted in a 56% reduction in the sulphur content of the coal. This coal sample (containing 1.8% sulphur) burned in the pilot-scale utility boiler to produce a flue gas containing 0.9 g SO_2/MJ of fuel input compared with 3.0 g SO_2 for the raw coal, both of which are much higher than the current Canadian national emission guideline.

RAPPORT FINAL SUR LES PROPRIÉTÉS DE COMBUSTION DU CHARBON BRUT ET DU CHARBON LAVÉ PROVENANT DE LA MINE PRINCE

par

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RÉSUMÉ

Les propriétés de combustion du charbon brut et du charbon lavé (charbon tout-venant) et celles de cinq charbons lavés à teneur différente, en provenance de la mine Prince, ont été comparées aux propriétés de combustion d'un charbon thermique bitumineux de l'Ouest canadien qui est actuellement disponible sur le marché. Ces charbons ont été soumis à des essais dans une chaudière expérimentale alimentée au charbon pulvérisé, propriété des Laboratoires de recherche sur l'énergie à Ottawa.

Deux des échantillons de charbon lavé provenaient de l'atelier de lavage de l'Electric Power Research Institute (EPRI) situé à Homer City aux É.-U. et les trois autres, de l'atelier de lavage des Laboratoires de recherche sur le charbon situé à Devon (Alberta). Les charbons ont été soumis à des analyses chimiques, physiques et thermogravimétriques. Tous les charbons se sont écoulés facilement dans le circuit de transport et de manutention expérimental.

Les charbons, dont le broyage était facile, ont donné un produit d'une granulométrie uniforme: ils s'enflammaient facilement et produisaient des flammes stables avec un taux de combustion supérieur à 96 %. Les taux de combustion les plus élevés (>99 %) ont été obtenus à partir des charges d'alimentation les plus finement broyées. Bien que les deux charbons lavés

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qui contenaient le moins de cendre aient donné les taux de combustion les plus élevés, le charbon brut dont le contenu combustible en cendre volante était le moindre a également affiché un taux de combustion supérieur à 99 %.

La cendre de chacun des charbons de la mine Prince était fluide et se scorifiait facilement dans le fond de la chaudière qui était recouvert d'une chemise de briques réfractaires tandis que les dépôts de cendre à la surface des écrans d'eau et du surchauffeur étaient légers et poudreux et ne posaient aucun problème d'encrassement.

Le contenu en soufre du charbon n'a pas diminué de façon significative avant que le contenu en cendres volantes ne soit réduit à moins de 7 %. Une réduction de 2,4 % du contenu en cendre a produit une réduction de 56 % du contenu en soufre du charbon. Cet échantillon de charbon (qui contenait 1,8 % en soufre) s'est consummé dans l'installation auxiliaire et a produit un gaz de carneau dont le contenu combustible était de 0,9 g SO_2MJ comparativement à 3,0 g SO_2/MJ pour le charbon brut. Ces deux taux de combustion sont de beaucoup supérieurs au taux d'émission permis stipulé dans les lignes directrices canadiennes.

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INTRODUCTION

As part of an International Energy Agency (IEA) research program, CANMET has agreed to conduct pilot-scale combustion trials on a number of raw and cleaned coals. The IEA Coal Cleanability and Combustion Characterization Project was formed to investigate the effect of coal beneficiation on the combustion properties of the less amenable thermal coals. Due to the diminishing quality of thermal coals and the increasing world recognition of environmental responsibilities, interest in the effects of coal beneficiation on the combustion performance of cleaned coals has significantly increased.

The first coal in this series to be tested at CANMET was from the Cape Breton Development Corporation's (CBDC) Prince mine, located on the Hub Seam in the Sydney coalfield. Cleaned coal test samples were produced from the Prince mine raw coal by the Electric Power Research Institute (EPRI) Homer City coal cleaning facility in the USA and the CANMET Coal Research Laboratories (CRL) coal cleaning facility in Devon, Alberta. These coal samples were shipped to Ottawa, Ontario, where combustion performance evaluation tests were carried out by CANMET's Energy Research Laboratories (ERL) in a pilot-scale pulverized-coal-fired research utility boiler. The combustion results obtained on the cleaned and raw Prince mine coals were compared with one another and with the test results obtained on a commercially available bituminous thermal coal sample (reference) from Western Canada.

This final report is a revised version of Division Report 86-30(IR). The report describes the objectives of the project and gives the analyses of the coals. Based on these analyses, the coals' apparent quality, combustion reactivity, and potential ash slagging and fouling properties are assessed. The facilities and equipment utilized and the operational procedures selected to evaluate the coals' actual combustion performance are then described and the actual pilot plant performance is compared with predicted values.

RESEARCH OBJECTIVES

The objectives of this project were:

1. To quantify coal quality, chemistry and petrography.

2. To determine coal comminution and handling characteristics.
3. To evaluate the combustion performance of the pulverized coal at two fineness levels and at an excess air level corresponding to 4% oxygen in the flue gases.
4. To characterize the particulate and gaseous pollutants generated during combustion.
5. To assess the slagging and fouling potential of the coal ash constituents on radiant heat transfer surfaces and superheater tubes.
6. To assess the electrical resistivity characteristics of the fly ash and the ease of fly ash collection by electrostatic precipitation.
7. To generate coal combustion charts, based on heat losses calculated from the coal analyses.

COAL CHARACTERISTICS

HANDLING AND PREPARATION

Samples of coal were delivered to CCRL in sealed 45-gallon drums. It was noted that trace element analyses of the Prince mine coal samples (Table 4) indicate a general trend to lower concentration of trace elements as the ash content of the coal is lowered; with the exception of the elements bromine and chlorine - which appear to increase in concentration as the ash content is lowered. It is suspected that this may be due to the techniques or solutions utilized in washing the coal. The coals with their "as received" moisture, were free flowing and no problems were experienced in feeding them through the pilot-scale coal handling system.

COMBUSTION REACTIVITY

The screen analyses and proximate, ultimate and ash analyses of the coal samples are listed in Tables 1 to 4. These analyses and the petrographic data given in Table 5 and Fig. 1 to 4 provide a guide for predicting "Combustion Reactivity". This term is generally understood as the ability of a coal to ignite readily and to produce a stable flame with acceptable carbon burn-out, without the necessity of support firing, when applied to the assessment of a potential thermal coal.

The volatile matter content of 31-42% suggests that these coals should ignite readily and the indicated percentage of reactive macerals in the coals (Table 5) is quite high (85-93%), which suggests that carbon burn-out of the coal should be excellent. Figure 1 illustrates the influence of different coal macerals on combustion reactivity and carbon burn-out. This figure indicates that the combustion efficiency of the Prince mine coal (raw and washed) should be higher than that obtained with the reference thermal coal, due to the greater amount of exinite and reactive vitrinite macerals.

Another method used to predict the reactivity of the coal is to determine its burn profile in air by thermogravimetric analysis (Fig. 3 and 4). The reference coal reached its highest devolatilization rate of 7.8%/min at a reaction temperature of 400°C whereas the Prince mine coal's highest devolatilization rate of 6.9%/min was not attained until a reaction temperature of 460°C was reached. This devolatilization rate (6.9%/min) was obtained with the washed coal containing 10.9% ash, compared with 5.9%/min at 456°C for the raw coal containing 24.5% ash. It was also noted that the Prince mine samples exhibited an initial devolatilization peak occurring between 300 and 400°C, suggesting either the possibility of an earlier ignition at a lower rate of devolatilization or indications of an oxidized coal. This initial peak was quite predominant in the raw coal sample, but diminished as the ash content of the coal samples decreased. These thermogravimetric analyses indicate that the combustion efficiency of the reference thermal coal is superior to that of the raw Prince mine coal as well as any of the Prince mine washed products.

Hence, because of this apparent conflicting reactivity evidence, it is not possible to give a reasonable prediction of the behaviour of the Prince mine coal samples without further corroborative support, such as pilot-scale combustion tests.

Combustion charts, based on the ultimate analyses of the raw Prince mine coal sample, are given in Appendix A. These charts provide a rapid, graphical means of determining boiler efficiency by the indirect ASME heat loss method.

HIGH TEMPERATURE ASH DEPOSITS

Two general types of high-temperature ash deposits can occur on the gas-side surfaces of coal-fired boilers:

1. Slagging - fused deposits that form on surfaces exposed predominantly to radiant heat transfer, such as on refractory furnace bottoms.
2. Fouling - high temperature bonded deposits that form on surfaces exposed predominantly to convective heat transfer, such as on superheater or reheater surfaces. Such deposits are not easily removed by soot-blowing procedures.

SLAGGING INDICATORS

The slagging potential of a coal can often be assessed by using indices or composite parameters to describe the nature and severity of the slag deposits (1). Two common indices for determining the slagging potential of the coal ash and furnace deposits are described below:

1. The base/acid ratio (B/A) is defined as:

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$$

where each oxide is expressed as a percentage of the total ash. A maximum of 0.5 for the base/acid ratio has been suggested for dry-bottom pulverized-fired units, although this is not a necessary restriction. Values below 0.27 indicate that slagging is an unlikely problem at normal furnace operating temperatures.

2. Potential slagging temperature (T_{ps}) is defined as:

$$T_{ps} = \frac{HT + 4IT}{5} \ ^{\circ}C$$

where IT is the minimum temperature at which initial ash deformation occurs (normally in a reducing atmosphere) and HT is the maximum temperature at

which hemispherical deformation occurs (normally in an oxidizing atmosphere). Temperature values greater than 1340°C indicate a low slagging potential, whereas values less than 1150°C indicate a severe slagging potential.

The base/acid ratio of 0.35 and the potential slagging temperature of 1194°C (Table 6), derived from the ash analysis and ash fusion data of the parent coal, suggest that the raw Prince mine coal will have a high slagging tendency and should be burned in a wet bottom furnace. The comparative indices for the washed Prince mine coal indicate an even higher and more severe slagging potential than was suggested for the raw Prince mine coal.

FOULING INDICATORS

Most indices are applied by categorizing the coal as having an "eastern type" or "western type" ash. The term "western type" is defined as an ash having more (CaO + MgO) than Fe_2O_3, on a per cent weight basis. On the above basis, the ashes from the Prince mine coals have (CaO + MgO): Fe_2O_3 ratios <0.20 and can be classified as "eastern type" ashes. This criterion depends solely on ash analyses and does not have any rank or geographic connotation.

There has been general agreement between research and operating practice that one of the dominant factors influencing superheater fouling is the sodium content of the coal ash. The following classification has been proposed:

Fouling category	% Na_2O in ash	
	"eastern type" ash $\frac{CaO + MgO}{Fe_2O_3}$ <1.0	"western type "ash $\frac{CaO + MgO}{Fe_2O_3}$ >1.0
Low	<0.5	<2.0
Medium	0.5 - 1.0	2.0 - 6.0
High	1.0 - 2.5	6.0 - 8.0
Severe	>2.5	>8.0

The Prince mine coal ashes have a Na_2O content ranging from 0.60 to 0.96% (Table 3), which indicates that they are in the medium fouling category of the "eastern type" ash.

Another possible indication of the fouling potential of a coal is based on its ash content, as outlined below:

Fouling potential	Ash content, wt %
Low	<15
Medium	15 - 25
High	>25

The raw Prince mine coal has an ash content of 24.5% (Table 2), indicating that it is in the medium fouling category whereas all of the washed Prince mine coals (<11% ash) would be considered to be in the low fouling category.

PILOT-SCALE RESEARCH BOILER

The CCRL pilot-scale research boiler is a pulverized coal-fired boiler incorporating two opposing low-swirl burners (Fig. 5). The furnace is U-shaped and consists of a vertical refractory shaft and a vertical steam boiler, which are connected at the bottom through a horizontal refractory tunnel. This boiler can be fired by the twin low-swirl burners located in four basic positions: A, B, C or D, more commonly known as the I, J, J_1 and U configurations, respectively. It is expected that highly reactive fuels will burn efficiently when fired in the I configuration, but for fuels that are difficult to burn, residence times and combustion zone temperatures can be increased by locating the twin burners in the U configuration. Intermediate residence times, if required, can be obtained by locating the burners in the J or J_1 configurations. It is estimated that at full load and with the burners located in the I configuration, the combustion chamber residence time will be about one second. This residence time will increase to about three seconds with the burners located in the U configuration. The combustion chamber heat release rate is about 0.35 $MJ/s/m^3$.

All of the sections of the furnace are designed to operate at pressures up to 2.5 kPa (250 mm of water). At the full-load firing rate of 2.5 GJ/h (0.7 MW), the boiler generates about 730 kg/h of steam at 690 kPa. It is possible to control the furnace exit temperature by adding cooled-wall

panels in the refractory shaft or by partially insulating the water walls of the boiler.

Crushed coal is supplied to the furnace from a 4500-kg hopper, mounted on an electronic weigh scale, through a variable-speed worm feeder to a ring-and-roller type of pulverizer, which is normally swept and pressurized by air at temperatures up to 230°C. If necessary, the pulverizer can be swept and pressurized with a mixture of air and flue gas at temperatures up to 400°C. The pulverizer contains a motor-driven classifier for controlling coal fineness and a riffle at the pulverizer outlet proportions the coal to each burner. Secondary air can be supplied to the burner at temperatures up to 260°C.

Combustion gases leave the furnace between 900°C-1300°C, then pass through a transition section, a test-air heater and a conventional three-pass air heater before entering a long horizontal sampling duct. A bypass from the air heater to the stack breeching and an additional heat exchanger surface in the sampling duct permit the gas temperature in the sampling duct to be varied from 150°C to 300°C.

A forced-draft fan supplies air to the air heater at 7 kPa (71 cm WC). The air, on leaving the heater, is divided into three systems: primary air to the pulverizer, secondary air to the burners and cooling air to the test air heater. The last stream, after leaving the test-air heater, can either be exhausted to the atmosphere or blended with the primary air supply to the pulverizer.

The research boiler is manually controlled, except for electrical interlocks to ensure that safe startup and shutdown procedures are followed. When burning high-grade coals, it has been possible to operate with as little as 1.0% O_2 and less than 100 ppm CO in the flue gases, with a smoke density of less than No. 1 Ringlemann.

EXPERIMENTAL PROCEDURES

OPERATING PROCEDURE

The following procedure, with minor variations in timing, was used for all trials:

1. Before each test, all boiler and air heater fireside surfaces were thoroughly cleaned by air lancing and the furnace bottom was lined with a refractory blanket. Sufficient coal was bunkered to provide 7 h continuous operation.
2. At 0800 h, the cold boiler was preheated with No. 2 fuel oil fired at 10 g/h, using two oil torches. Excess air was adjusted to provide 5% O_2 in the flue gas and the boiler was allowed to stabilize at full steaming rate and pressure. All continuous monitoring instruments were activated.
3. At 0920 h, pulverized coal was fed to the boiler at a specified classifier speed, mill temperature and excess air level. One oil torch was left in operation.
4. After flame stability was established, the oil torch was removed, allowing the boiler to operate on pulverized coal only.
5. At 1100 h, scheduled testing was begun. Boiler panel readings were monitored continuously and recorded every half hour. A specified coal feed rate, coal fineness and excess air level were maintained as closely as possible for the test duration.
6. By 1600 h, all measurements were completed and the boiler was shut down.
7. The furnace was allowed to cool overnight. The furnace bottom was then removed, the duct works were dismantled and the ash in the furnace bottom and duct work were photographed, collected, weighed and sampled.

PARAMETERS OF COMBUSTION PERFORMANCE

The following combustion performance parameters were measured at the sampling stations illustrated in Fig. 4:

1. Coal quality of a composite sample was taken from the crushed coal feed at the pulverizer inlet. Station 1.
2. Moisture and sieve analyses of pulverized coal samples were taken at the pulverizer outlet. Station 2.
3. O_2 content of the flue gas was measured continuously by a Dynatron oxygen analyzer and a paramagnetic monitor. Stations 8 and 10, respectively.

4. NO content of the flue gas was measured continuously by a chemiluminescent monitor. Station 10.
5. CO and CO_2 contents of the flue gas were measured continuously by infrared monitor. Station 10.
6. SO_2 and SO_3 contents of the flue gas were measured continuously by ultra-violet and absorption colorimetric methods. Stations 10 and 13, respectively.
7. Low-temperature corrosion potential was measured by three mild steel probes which were inserted simultaneously into the flue gas stream and maintained at three different temperatures for the duration of the combustion test. Station 9.
8. Fly-ash loading was measured by an isokinetic sampling system, three samples per test. These samples were analyzed for carbon content and dust loading. Stations 15 and 16.
9. Aerodynamic size distribution was determined in a fractionating sampler and in a Cascade cyclone sampler. Station 12.
10. Fouling of heat-transfer surfaces was evaluated by visual examination and chemical composition of ash build-up on a simulated superheater, installed immediately downstream of the screen tubes. Station 7.
11. Slagging propensity was determined by examining the thickness, physical structure, chemical composition and melting characteristics of ash deposits selected from various parts of the furnace. Stations 3 to 6.
12. Fly-ash resistivities were measured by an in situ, point-plane resistivity apparatus at flue gas temperatures of approximately 300°C at Station 11, and 180°C at Station 14.

COMBUSTION PERFORMANCE

COAL COMMINUTION

The Prince mine coals were crushed, dried, metered and pulverized to the selected degree of fineness without difficulty. The CCRL coal drying and grinding system is illustrated in Fig. 6. The pulverized coals were then transported directly to the burners without moisture separation from the carrying air. The size distribution of the pulverized coals for each of the

trials is shown in Tables 7 and 8. A coarse grind (70 to 80% minus 200 mesh) was maintained for the trials (C-1A to C-7A) in Table 7, while a finer grind (>80% minus 200 mesh) was maintained for the trials (C-1B to C-7B) in Table 8.

BOILER OPERATION AND FLAME CHARACTERISTICS

The boiler operating conditions, shown in Tables 7 and 8, remained essentially constant between 2000 and 2300 MJ/h input for all furnace trials. The flame was bright, clean and stable under reasonably steady-state conditions and an oil support flame was required for only a few minutes at the start of each trial. It should be noted that the coals were fired in the I furnace configuration for all of the furnace trials.

GASEOUS EMISSIONS

The average flue gas analyses for each combustion trial are summarized in Tables 7 and 8. The carbon monoxide levels, at less than 100 ppm, do not constitute either an emission problem or a significant thermal penalty.

The sulphur dioxide emissions from this coal were 0.91 to 3.09 g SO_2/MJ, which is much higher than the current Canadian national emission guideline of 0.258 g SO_2/MJ of fuel input for new combustion systems (2). The nitric oxide emission rates of 0.38 to 0.42 g NO/MJ are well above the current Canadian national emission guideline of 0.168 g NO/MJ of fuel input, but tnis level is specific to the CCRL equipment and it can be significantly improved through the use of modern low-NO_x burner technology.

FLY ASH CHARACTERISTICS AND COAL BURN-OUT

The mass loadings, aerodynamic particle size and combustible content of the fly ash for each trial are summarized in Tables 9 and 10. These data indicate, as expected, that the fly ash loadings are higher for the coals containing a greater percentage of ash. It is also clearly evident that the more finely ground coal results in a lower combustible content in the fly ash. This lower combustible content obviously effects the calculated combustion efficiency of the higher ash coals more acutely than those containing little ash.

In general, high electrical resistivity (>10 log ohm-cm) indicates that precipitated fly ash will retain a strong electrical charge and repel any similarly charged particles or generate a back corona within the deposit; precipitation, conversely, is therefore difficult. A low resistivity (< 7 log ohm-cm) fly ash will readily precipitate but will not adhere strongly to the collecting plates and will easily be re-entrained in the flue gas. Intermediate resistivity values of approximately 8 to 9 log ohm-cm are considered to yield the best precipitator efficiencies.

The measured in situ electrical resistivity of the fly ash from each of the trials, with one exception, was approximately 5 log ohm-cm. This one exception was the finely ground raw coal (trial 2B) which had an electrical resistivity >7.0 log-ohm cm. It is suspected that this was due to the much lower combustible content of the fly ash.

ASH SLAGGING AND FOULING

The calculated potential slagging temperature and the base/acid ratio shown in Table 6 indicate a high-to-severe slagging propensity for the Prince mine coal samples compared with the medium propensity of the reference coal. This severe slagging of the Prince mine coal samples was confirmed by the combustion trials (Fig. 6 and 7). The analytical data on the furnace products collected from the combustion trials are tabulated in Tables 13 to 16. The calculated slagging potentials of these products, shown in Tables 17 to 20, also confirm the predicted high-to-severe slagging potential of the Prince mine coal. The analytical data on the parent coal ashes predicted a low-to-medium fouling tendency which was confirmed by the powdery, loosely adherent deposits formed on the water-walls and convective heat transfer surfaces (Fig. 8 and 9). It was also noted that, as the ash content of the coal was reduced, the amount of slag formed in the furnace bottom (Fig. 7) and the amount of ash collected on the superheater tubes (Fig. 9) were reduced dramatically, without causing any material changes to the furnace operating temperatures (Tables 7 and 8).

CONCLUSIONS

The Prince mine coals handled and flowed without difficulty, resulting in a ground coal product which ignited readily to produce stable combustion flames, quite similar in appearance to one another and to the reference thermal coal.

The petrographic data and coal analyses suggested that the carbon burn-out from the Prince mine coals (raw and washed) should be excellent, but thermogravimetric analyses indicated that the combustion reactivity of these coals will be lower than that of the reference coal. Combustion studies in the utility boiler indicated that the raw Prince mine coal can be burned to less than 6% combustible in the fly ash with a coarse grind (72% minus 200 mesh) and less than 2.5% combustible content with a fine grind (97% minus 200 mesh); whereas the washed coals burned to combustible contents of 9 to 24% in the fly ash, varying with the grind and ash content of the coal. These figures compare to a 2.1% combustible content in the fly ash from the thermal reference coal, containing 10.5% ash and fired at a grind of 90% minus 200 mesh, to give a 99.9% combustion efficiency (higher than any of the Prince mine coal samples).

Washing the Prince mine coal reduced the sulphur content of the coal by 6% to 56% (depending on the amount of ash removed). The overall reduction in SO_2 evolved in the flue gas (g/MJ of fuel input) compared with the raw coal varied from 34% to 70%, with the highest SO_2 reduction as a result of the highest ash removal. Moreover, the lowest emission rate of 0.906 g SO_2/MJ is still well above the current Canadian emission guideline of 0.258 g SO_2/MJ of fuel input.

The tendency of the coal ash to slag was predicted to be high to severe from the analytical data on the parent Prince mine raw and washed coal samples. This prediction was confirmed by the fluid slag produced in the refractory-lined furnace bottom. The analytical data also indicated a low-to-medium fouling tendency, which was consistent with the powdery, easily removed ash material deposited on the water-walls and the superheater tubes during the combustion trials. As expected, reducing the ash content of the Prince mine coal dramatically reduced the amount of slag collected in the furnace bottom and also the ash collected on the superheater tubes, without visible effects on the furnace operating temperatures.

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Table 1 - Screen analysis of Prince mine coal samples

Screen size (mm)	Weight % (cumulative)						
	Ref. coal C-1	Raw coal C-2	Devon washed C-3	Devon washed C-4	EPRI washed C-5	Devon washed C-6	EPRI washed C-7
+25.4	1.75	9.71	-	-	-	-	0.26
+19.1	3.70	15.12	-	-	0.18	-	0.96
+12.7	9.84	25.98	0.99	0.31	2.84	0.49	7.36
+6.4	28.86	48.64	12.57	8.00	19.23	10.13	28.64
+3.2	54.32	70.14	53.51	42.05	56.22	50.43	59.82
-3.2	45.68	9.86	46.49	57.95	43.78	49.57	40.18
Bulk density (kg/m^3)	881	851	692	649	705	672	689
% moisture	8.4	9.2	6.3	7.1	6.7	6.4	7.1

Table 2 - Coal analyses

Component	Ref. coal	Prince Mine coals						Pacific rim specifications	
		Raw coal	Devon washed		EPRI washed	Devon washed	EPRI washed		
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	KECO	EPDC
Moisture, wt %									
As received	6.04	1.56	7.55	7.68	1.54	6.46	2.00	<15	<10
Equilibrium	8.72	6.34	6.17	5.96	5.69	5.77	6.16	-	-
Proximate, wt % (dry)									
Ash	10.50	24.54	10.88	7.64	6.97	5.21	2.41	<17	<20
Volatile matter	33.39	31.14	39.32	42.43	37.90	32.17	37.27	22-36	$\frac{VM}{FC} \geq 0.4$
Fixed carbon	55.11	44.32	49.80	49.93	55.13	62.62	60.32	50-60	
Ultimate, wt % (dry)									
Carbon	71.04	58.64	71.57	75.09	74.79	77.72	80.20	-	-
Hydrogen	4.46	4.10	4.93	5.00	5.04	5.29	5.39	-	-
Sulphur	0.22	4.21	3.96	3.28	3.92	2.89	1.84	<1.0	<1.0
Nitrogen	1.16	1.34	1.53	1.72	1.70	1.65	1.81	<2.0	<1.8
Ash	10.50	24.54	10.88	7.64	6.97	5.21	2.41	-	-
Oxygen (by diff)	12.62	7.17	7.13	7.27	7.58	7.24	8.35	-	-
Calorific value, MJ/kg	28.20	24.21	29.56	30.95	31.52	32.09	33.46	>25.12	>25.12
Hardgrove grindability index	52	69	58	56	61	57	58	>45	>45
Chlorine in coal, wt %	0.01	0.30	0.35	0.39	0.30	0.47	0.43	-	-
Free swelling index	N.A.*	2.5	5.5	6.0	5.0	5.0	3.5	-	-
Ash Fusibility, °C									
Reducing atmosphere									
Initial deformation	1229	1138	1071	1082	1091	1102	1088	>1250	-
Spherical softening	1318	1374	1099	1127	1113	1121	1138	-	-
Hemispherical deformation.	1374	1391	1246	1293	1249	1154	1318	-	-
Fluid temperature	>1482	1421	1332	1360	1382	1271	1441	-	-
Oxidizing atmosphere									
Initial deformation	1279	1352	1385	1382	1371	1388	1316	-	-
Spherical softening	1368	1404	1418	1413	1416	1435	1379	-	>1200
Hemispherical deformation.	1432	1421	1421	1421	1421	1440	1393	-	-
Fluid temperature	>1482	1443	1424	1421	1432	1449	1421	-	>1300

*Non-agglomerating

Table 3 - Analyses of parent coal ash

Major elemental oxides (wt%)	Ref. coal	Prince raw	Devon washed		EPRI washed	Devon washed	EPRI washed
	C-1	C-2	C-3	C-4	C-5	C-6	C-7
SiO_2	60.01	47.92	37.31	33.71	27.04	22.40	30.80
Al_2O_3	18.09	23.50	21.61	19.45	15.59	15.17	21.80
Fe_2O_3	3.60	19.76	33.42	36.16	49.80	53.99	32.76
TiO_2	0.86	0.82	0.82	0.84	0.72	0.70	0.99
P_2O_5	0.25	0.07	0.03	0.05	0.05	0.00	0.03
CaO	7.85	1.30	1.10	1.78	1.14	1.67	3.76
MgO	1.59	1.02	0.76	0.76	0.47	0.69	1.08
SO_3	3.90	1.63	0.70	1.98	1.28	1.05	3.26
Na_2O	1.35	0.61	0.62	0.75	0.70	0.96	0.94
K_2O	0.41	2.48	1.81	1.60	1.07	0.93	1.41
BaO	0.15	-	0.16	0.22	-	0.15	-
SrO	0.11	-	0.01	0.01	-	-	0.03
L.O.F.	0.81	0.77	0.53	0.88	0.78	0.59	0.73

Table 4 - Trace elements determined in coal samples (ppm)

	Neutron activation analyses, ppm (dry basis)						
	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Antimony (Sb)	0.7	1.7	1.0	0.8	1.0	0.7	0.3
Arsenic (As)	3.1	106	64.9	48.1	63.1	38.1	18.7
Barium (Ba)	265	86	39	20	36	<15	<14
Bromine (Br)	0.4	52.8	61.3	62.4	67.9	68.4	73.5
Caesium (Cs)	0.5	3.0	1.4	0.8	0.4	<0.3	<0.2
Cerium (Ce)	14.3	30.0	15.0	10.8	9.1	7.7	4.9
Chlorine (Cl)	29.0	2770	3060	3280	3490	3440	3900
Chromium (Cr)	5.4	30.6	15.0	10.0	10.6	11.0	6.6
Cobalt (Co)	1.7	6.9	4.0	3.0	3.7	2.2	1.1
Copper (Cu)	8.7	36.2	13.4	14.3	19.3	12.2	10.2
Dysprosium (Dy)	1.1	1.6	1.1	1.0	1.0	0.8	0.7
Europium (Eu)	0.2	0.4	0.3	0.2	0.2	0.2	0.1
Hafnium (Hf)	1.0	0.9	0.6	0.4	0.3	<0.2	<0.1
Holmium (Ho)	0.2	0.5	<0.5	<0.5	0.2	<0.5	<0.1
Iodine (I)	<0.5	<0.4	1.6	1.9	0.3	1.5	0.4
Lanthanum (La)	6.5	15.3	7.7	5.3	4.6	3.4	2.5
Lutecium (Lu)	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Manganese (Mn)	31.1	91.0	34.8	33.0	27.2	30.5	14.7
Molybdenum (Mo)	2.1	7.4	5.7	4.8	5.3	4.3	2.6
Neodymium (Nd)	4.7	9.1	7.0	6.4	3.5	<2.8	3.2
Nickel (Ni)	<26	<40	<47	<43	<30	<38	<17
Rubidium (Rb)	<4.3	33.0	12.0	<190	5.7	<6.4	<2.8
Samarium (Sm)	1.1	2.1	1.3	1.0	0.9	0.8	0.5
Scandium (Sc)	1.7	4.9	2.5	2.0	1.7	1.4	0.8
Strontium (Sr)	130	130	54.0	<32.0	48.0	<30	<29
Tantalum (Ta)	<0.2	0.3	0.1	<0.1	0.1	<0.1	<0.1
Terbium (Tb)	<0.2	<0.2	<0.6	<0.2	<0.1	<0.2	0.1
Thorium (Th)	2.5	3.9	1.9	1.5	1.0	1.0	0.6
Uranium (U)	1.4	1.0	0.6	0.5	0.4	0.4	0.2
Vanadium (V)	10.5	46.2	27.0	23.0	24.3	18.1	10.7
Ytterbium (Yb)	2.1	1.0	0.6	0.3	0.5	0.3	0.2
Zinc (Zn)	<10	37.0	29.0	54.0	16.0	23.0	14.0

Table 5 - Petrographic examination of coal macerals

Maceral form	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Reactives							
Exinite	3.9	6.0	6.8	4.8	5.0	5.8	5.1
Vitrinite	64.8	77.7	75.9	79.9	81.4	82.1	86.2
Reactive semi-fusinite ...	5.5	1.0	2.0	1.7	1.7	1.3	1.2
Sub-total	74.2	84.7	84.7	86.4	88.4	89.2	92.5
Inerts							
Fusinite	6.5	2.3	2.3	3.2	3.0	3.0	1.8
Semi-fusinite	11.0	2.1	3.9	3.5	3.4	2.5	2.5
Micrinite	2.4	0.9	2.0	1.9	0.8	1.8	1.4
Mineral matter	5.9	10.0	7.1	5.0	4.7	3.5	1.8
Sub-total	25.8	15.3	15.3	13.6	11.9	10.8	7.5
Mean reflectance, %	0.60	0.70	0.73	0.76	0.71	0.74	0.70

Table 6 - Comparative indices of the slagging potential of parent coals

Slagging propensity	Reference limits	Parent coal ash						
		C-1	C-2	C-3	C-4	C-5	C-6	C-7
Base/Acid (B/A) Ratio								
Low	<0.15	-	-	-	-	-	-	-
Medium	0.15 - 0.30	0.19	-	-	-	-	-	-
High	0.27 - 0.50	-	0.35	-	-	-	-	-
Severe	>0.50	-	-	0.63	0.76	1.23	1.52	0.75
Potential slagging temp (Tps, °C)								
Low	>1340	-	-	-	-	-	-	-
Medium	1340 - 1230	1270	-	-	-	-	-	-
High	1230 - 1150	-	1194	-	1150	1157	1170	-
Severe	<1150	-	-	1141	-	-	-	1149

Table 7 - Boiler operating conditions (coarse grind)

Components	C-1A	C-2A	C-3A	C-4A	C-5A	C-6A	C-7A
Furnace configuration	I	I	I	I	I	I	I
Fuel rate, kg/h	75.0	85.7	69.8	67.9	67.1	67.6	69.5
Fuel moisture, wt %	0.37	0.23	0.64	0.72	0.00	0.00	0.00
Coal fineness, wt % (Cdn std)							
+100 mesh	0.3	0.6	0.6	0.4	0.7	0.7	0.5
-100 + 140 mesh	5.3	3.1	9.6	4.8	2.1	7.6	2.7
-100 + 200 mesh	22.4	23.3	17.5	17.5	17.1	19.5	24.5
-200 + 325 mesh	48.0	56.8	41.5	45.6	63.5	52.7	59.2
-325 + 400 mesh	10.4	9.2	16.1	17.7	7.9	10.4	5.8
-400 mesh	13.6	7.0	14.7	14.0	8.8	9.1	7.3
-200 mesh	72.0	73.0	72.3	77.3	80.2	72.2	72.3
Heat input, MJ/h	2107	2070	2050	2086	2115	2169	2325
Furnace exit temp, °C	1000	987	>802	>832	>835	>794	873
Air temperature, °C							
Pulverizer in	209	213	209	199	198	200	200
Pulverizer out	111	111	116	106	111	108	111
Secondary	268	263	243	236	240	236	246
Steam rate, kg/MJ	0.209	0.196	0.205	0.206	0.217	0.199	0.195
Flue gas rate, Nm^3/MJ	0.306	0.310	0.309	0.308	0.302	0.308	0.303
Flue gas analyses, volume							
CO_2 %	14.9	14.6	14.7	14.6	14.5	14.5	14.5
O_2 %	4.0	4.0	4.0	4.0	4.0	4.0	4.1
CO ppm	43	77	62	62	59	56	56
NO ppm	833	922	941	972	1011	955	964
SO_2 ppm	220	3483	1967	1773	2010	1651	1076
SO_3 ppm	-	2.2	2.6	2.8	4.2	2.7	1.7
Emission rates, g/MJ							
NO	0.341	0.383	0.390	0.400	0.409	0.393	0.392
SO_2	0.192	3.088	1.740	1.560	1.735	1.453	0.934

Table 8 - Boiler operating conditions (fine grind)

Components	C-1B	C-2B	C-3B	C-4B	C-5B	C-6B	C-7B
Furnace configuration	I	I	I	I	I	I	I
Fuel rate, kg/h	78.8	86.3	71.0	69.5	67.0	67.7	65.1
Fuel moisture, wt %	0.00	0.79	1.20	1.2	0.00	0.00	0.00
Coal fineness, wt % (Cdn std)							
+100 mesh	0.1	0.7	0.3	0.5	0.4	0.1	0.4
-100 + 140 mesh	1.4	1.0	5.5	1.5	2.4	2.7	1.5
-140 + 200 mesh	9.1	1.7	12.1	7.6	6.6	15.0	12.3
-200 + 325 mesh	59.4	60.6	51.1	53.3	69.5	65.9	75.0
-325 + 400 mesh	13.7	20.9	18.3	20.8	10.0	6.3	3.9
-400 mesh	16.3	15.1	12.7	16.2	11.0	10.0	6.9
-200 mesh	89.4	96.6	82.1	90.3	90.5	82.2	85.8
Heat input, MJ/h	2101	2073	2074	2125	2112	2172	2178
Furnace exit temp, °C	1023	933	>838	>836	898	>736	937
Air temperature, °C							
Pulverizer in	212	217	206	206	209	203	205
Pulverizer out	119	111	112	114	123	110	118
Secondary	259	271	242	250	255	242	253
Steam rate, kg/MJ	0.198	0.184	0.208	0.208	0.207	0.199	0.201
Flue gas rate, Nm^3/MJ	0.306	0.312	0.309	0.308	0.302	0.308	0.300
Flue gas analyses, Volume							
CO_2 %	14.9	14.5	14.7	14.6	14.6	14.5	14.9
O_2 %	4.0	4.1	4.0	4.0	4.0	4.0	3.9
CO ppm	40	45	62	66	100	42	48
NO ppm	859	1000	957	998	942	1031	1014
SO_2 ppm	216	3334	2224	1886	2195	1551	1057
SO_3 ppm	0.1	1.9	2.6	2.4	2.4	1.5	1.7
Emission rates, g/MJ							
NO	0.352	0.418	0.396	0.411	0.381	0.425	0.407
SO_2	0.189	2.973	1.967	1.659	1.895	1.365	0.906

Table 9 - Fly ash characteristics (coarse grind)

Components	C-1A	C-2A	C-3A	C-4A	C-5A	C-6A	C-7A
Precipitator inlet loading,							
g/Nm^3	2.50	6.94	1.95	2.03	1.50	1.24	1.29
g/MJ	0.77	2.15	0.60	0.62	0.45	0.38	0.39
Combustible content, wt % ...	5.71	5.59	20.6	13.9	16.0	16.1	24.4
Aerodynamic particle size, wt %							
+30 µm	-	-	3	9	1	4	11
+10 µm	53	45	53	56	45	48	42
+1 µm	98	97	96	96	95	95	94
Electrical resistivity log ohm-cm							
@ 165°C	7.73	5.11	4.75	4.73	-	4.78	4.83
@ 330°C	5.18	5.38	5.20	5.18	5.46	5.27	5.43
Combustion efficiency, %* ...	99.24	97.98	96.77	98.66	98.58	98.95	99.22

*Combustion efficiency, % = $100 - \frac{33.727\ AC}{(100-C)\ Q}$

where: A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = Calorific value of coal feed, MJ/kg (dry basis)

Table 10 - Fly ash characteristics (fine grind)

Components	C-1B	C-2B	C-3B	C-4B	C-5B	C-6B	C-7B
Precipitator inlet loading,							
g/Nm^3	2.26	8.24	2.69	2.07	1.57	1.21	0.81
g/MJ	0.69	2.57	0.83	0.64	0.47	0.37	0.24
Combustible content, wt % ...	2.14	2.44	20.18	13.52	19.76	8.54	13.88
Aerodynamic particle size, wt %							
+30 µm	-	6	3	5	1	7	5
+10 µm	55	44	51	54	43	37	41
+1 µm	98	98	96	97	95	94	93
Electrical resistivity log ohm-cm							
@ 165°C	10.18	-	4.76	4.74	5.11	4.83	5.15
@ 330°C	7.48	7.76	5.15	5.26	5.34	5.18	5.48
Combustion efficiency, %* ...	99.86	99.15	96.86	98.70	98.16	99.49	99.61

*Combustion efficiency, % = $100 - \frac{33.727\ AC}{(100-C)\ Q}$

where: A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = Calorific value of coal feed, MJ/kg (dry basis)

Table 11 - Fly ash analyses (coarse grind)

Major elemental oxides (wt %)	Combustion trial						
	C-1A	C-2A	C-3A	C-4A	C-5A	C-6A	C-7A
SiO_2	58.91	47.48	32.40	32.42	29.75	25.08	32.99
Al_2O_3	20.08	25.22	21.58	21.52	20.05	17.74	22.53
Fe_2O_3	4.27	18.33	32.57	35.27	39.62	46.03	28.08
TiO_2	1.11	0.92	1.07	0.95	1.07	0.94	1.12
P_2O_5	0.44	0.07	0.12	0.08	0.11	0.08	0.11
CaO	8.30	1.36	2.22	2.27	2.03	2.43	4.34
MgO	1.51	1.05	1.10	0.65	0.82	0.50	1.21
SO_3	0.45	1.38	2.45	1.39	2.43	2.29	3.32
Na_2O	1.56	0.88	1.23	1.11	1.26	1.25	2.37
K_2O	0.46	2.69	1.89	1.78	1.43	1.29	1.98
BaO	0.61	-	-	0.29	0.13	0.33	-
SrO	0.15	0.27	0.02	0.02	0.02	0.02	0.05

Table 12 - Fly ash analyses (fine grind)

Major elemental oxides (wt %)	Combustion trial						
	C-1B	C-2B	C-3B	C-4B	C-5B	C-6B	C-7B
SiO_2	56.94	47.55	33.61	31.58	27.48	25.57	33.08
Al_2O_3	19.79	25.66	21.89	21.15	19.84	18.35	22.71
Fe_2O_3	4.52	18.03	34.17	35.50	41.50	44.55	26.87
TiO_2	1.13	0.93	0.99	0.99	1.04	0.96	1.18
P_2O_5	0.44	0.11	0.08	0.08	0.08	0.12	0.08
CaO	9.48	1.38	1.88	2.42	1.95	2.58	4.66
MgO	1.89	1.31	0.89	0.91	0.91	0.61	1.19
SO_3	0.73	0.96	1.03	1.94	2.23	3.17	3.81
Na_2O	1.23	0.75	1.03	1.12	1.36	1.25	2.29
K_2O	0.46	2.53	1.91	1.80	1.50	1.31	2.09
BaO	0.76	0.26	-	-	0.18	0.26	-
SrO	0.16	0.03	0.02	0.02	0.02	0.02	0.06

Table 13 - Analyses of furnace bottom deposits (coarse grind)

	Combustion trial						
	C-1A	C-2A	C-3A	C-4A	C-5A	C-6A	C-7A
Major elemental oxides (wt %)							
SiO_2	65.36	46.96	34.29	33.40	27.59	32.66	45.01
Al_2O_3	18.74	22.43	20.83	19.65	23.45	20.05	22.98
Fe_2O_3	3.89	22.40	38.35	39.73	34.18	40.36	24.15
TiO_2	0.67	0.62	0.68	0.68	0.66	0.53	0.87
P_2O_5	0.26	0.01	0.03	-	0.03	0.01	0.02
CaO	6.84	3.08	1.14	1.91	3.23	1.88	3.07
MgO	1.15	0.80	0.65	0.57	0.67	0.58	0.77
SO_3	0.43	0.08	0.28	0.24	0.16	0.14	0.29
Na_2O	0.54	0.85	0.49	0.40	0.65	0.68	0.62
K_2O	0.32	1.36	1.32	1.13	0.92	0.77	1.54
BaO	0.07	-	0.35	-	-	-	-
SrO	0.09	-	-	-	-	-	0.01
Ash fusibility, °C							
Reducing atmosphere							
Initial deformation	1260	1118	1038	1071	1091	1078	1085
Spherical softening	1293	1191	1071	1146	1169	1105	1135
Hemispherical deformation .	1382	1204	1188	1177	1250	1132	1177
Fluid temperature	>1482	1298	1316	1299	1347	1263	1313
Oxidizing atmosphere							
Initial deformation	1263	1202	1388	1371	1218	1220	1332
Spherical softening	1363	1384	1421	1421	1389	1403	1404
Hemispherical deformation .	1432	1406	1424	1424	1403	1414	1418
Fluid temperature	>1482	1432	1429	1429	1422	1427	1432

Table 14 - Analyses of furnace bottom deposits (fine grind)

	Combustion trial						
	C-1B	C-2B	C-3B	C-4B	C-5B	C-6B	C-7B
Major elemental oxides (wt %)							
SiO_2	62.11	48.89	37.78	32.52	33.00	22.57	35.78
Al_2O_3	18.90	22.37	22.43	19.94	23.57	14.56	27.38
Fe_2O_3	4.60	20.52	33.10	39.06	33.12	58.65	23.67
TiO_2	0.63	0.79	0.56	0.48	0.90	0.50	0.78
P_2O_5	0.27	0.02	0.02	0.03	0.03	0.05	0.03
CaO	7.65	1.39	1.51	2.83	4.45	1.05	4.91
MgO	1.15	0.73	0.58	0.58	0.45	-	1.11
SO_3	0.34	0.26	0.11	0.21	0.37	0.30	0.10
Na_2O	0.51	0.47	0.54	0.54	0.61	0.52	0.85
K_2O	0.37	2.10	1.08	0.86	0.88	0.68	0.98
BaO	0.49	0.25	-	-	0.22	-	-
SrO	0.08	0.01	-	-	0.02	0.01	-
Ash fusibility, °C							
Reducing atmosphere							
Initial deformation	1254	1096	1091	1083	1082	1102	1153
Spherical softening	1299	1124	1121	1094	1129	1116	1180
Hemispherical deformation .	1388	1274	1132	1105	1207	1124	1193
Fluid temperature	>1482	1354	1317	1250	1335	1268	1301
Oxidizing atmosphere							
Initial deformation	1268	1366	1244	1228	1366	1441	1244
Spherical softening	1335	1396	1424	1392	1402	1452	1406
Hemispherical deformation .	1460	1424	1432	1406	1413	1454	1416
Fluid temperature	>1482	1441	1454	1422	1432	1460	1435

Table 15 - Analyses of superheater deposits (coarse grind)

	Combustion trial						
	C-1A	C-2A	C-3A	C-4A	C-5A	C-6A	C-7A
Major elemental oxides (wt %)							
SiO_2	58.39	49.76	30.15	29.82	23.91	23.69	39.72
Al_2O_3	18.88	21.29	18.41	17.97	15.74	14.72	18.40
Fe_2O_3	4.67	19.96	43.87	43.71	53.26	52.85	30.75
TiO_2	1.10	0.57	0.70	0.66	0.65	0.33	0.35
P_2O_5	0.40	0.06	0.03	0.04	-	0.02	0.06
CaO	8.80	1.43	1.05	1.40	0.92	1.60	2.49
MgO	1.13	1.04	0.88	0.67	0.53	0.49	0.78
SO_3	1.65	0.72	1.29	1.16	1.48	0.90	1.95
Na_2O	1.58	0.82	0.64	0.64	0.71	0.70	1.13
K_2O	0.37	1.98	1.29	1.26	0.90	0.61	1.29
BaO	0.62	-	0.31	-	-	-	-
SrO	0.14	-	-	-	-	-	-
Ash fusibility, °C							
Reducing atmosphere							
Initial deformation	1232	1116	1105	1082	1093	1089	1110
Spherical softening	1285	1191	1116	1138	1113	1158	1123
Hemispherical deformation	1329	1207	1129	1227	1141	1167	1151
Fluid temperature	>1482	1314	1271	1288	1249	1266	1309
Oxidizing atmosphere							
Initial deformation	1277	1236	1393	1385	1396	1218	1240
Spherical softening	1335	1408	1424	1421	1435	1441	1408
Hemispherical deformation	1410	1419	1429	1429	1443	1446	1414
Fluid temperature	>1482	1430	1435	1432	1452	1454	1435

Table 16 - Analyses of superheater deposits (fine grind)

	Combustion trial						
	C-1B	C-2B	C-3B	C-4B	C-5B	C-6B	C-7B
Major elemental oxides (wt %)							
SiO_2	59.45	49.36	36.48	34.22	25.10	21.64	32.92
Al_2O_3	20.16	22.43	19.22	18.66	15.65	14.23	20.91
Fe_2O_3	4.39	19.50	37.04	39.20	47.49	58.67	33.07
TiO_2	0.88	0.76	0.46	0.53	0.48	0.54	0.85
P_2O_5	0.31	0.02	0.03	0.05	0.09	0.04	0.05
CaO	9.94	1.25	1.36	1.86	1.00	1.08	2.78
MgO	1.38	1.04	0.63	0.72	0.50	0.28	0.71
SO_3	1.65	0.64	0.63	0.87	0.51	1.60	3.18
Na_2O	0.88	0.71	0.63	0.70	1.09	0.68	1.31
K_2O	0.30	1.85	1.07	1.04	0.81	0.75	1.56
BaO	0.47	-	-	-	-	0.24	-
SrO	0.12	-	-	-	-	-	0.02
Ash fusibility, °C							
Reducing atmosphere							
Initial deformation	1199	1121	1107	1083	1118	1107	1085
Spherical softening	1285	1207	1169	1134	1207	1118	1121
Hemispherical deformation	1360	1220	1186	1139	1215	1127	1216
Fluid temperature	1404	1352	1368	1263	1298	1235	1310
Oxidizing atmosphere							
Initial deformation	1252	1238	1277	1220	1226	1413	1346
Spherical softening	1329	1403	1448	1400	>1454	1468	1396
Hemispherical deformation	1371	1414	>1454	1416	>1454	1474	1410
Fluid temperature	>1482	1430	>1454	1435	>1454	>1482	1413

Table 17 - Comparative indices of slagging potential
- furnace bottom deposits (coarse grind)

Slagging propensity	Reference limits	Original ash source - coarse grind						
		Ref. coal C-1A	C-2A	C-3A	C-4A	C-5A	C-6A	C-7A
Base/Acid (B/A) Ratio								
Low	<0.15	-	-	-	-	-	-	-
Medium	0.15 - 0.30	0.15	-	-	-	-	-	-
High	0.27 - 0.50	-	0.41	-	-	-	-	0.44
Severe	>0.50	-	-	0.75	0.81	0.77	0.83	-
Potential slagging temp (Tps, °C)								
Low	>1340	-	-	-	-	-	-	-
Medium	1340 - 1230	1294	-	-	-	-	-	-
High	1230 - 1150	-	1176	-	-	1153	-	1152
Severe	<1150	-	-	1115	1142	-	1145	-

Table 18 - Comparative indices of slagging potential
- furnace bottom deposits (fine grind)

Slagging propensity	Reference limits	Original ash source - fine grind						
		Ref. coal C-1B	C-2B	C-3B	C-4B	C-5B	C-6B	C-7B
Base/Acid (B/A) Ratio								
Low	<0.15	-	-	-	-	-	-	-
Medium	0.15 - 0.30	0.17	-	-	-	-	-	-
High	0.27 - 0.50	-	0.35	-	-	-	-	0.49
Severe	>0.50	-	-	0.61	0.83	0.69	1.62	-
Potential slagging temp (Tps, °C)								
Low	>1340	-	-	-	-	-	-	-
Medium	1340 - 1230	1295	-	-	-	-	-	-
High	1230 - 1150	-	1162	1159	-	-	1172	1206
Severe	<1150	-	-	-	1148	1148	-	-

Table 19 - Comparative indices of slagging potential
- superheater deposits (coarse grind)

Slagging propensity	Reference limits	Original ash source - coarse grind						
		Ref. coal C-1A	C-2A	C-3A	C-4A	C-5A	C-6A	C-7A
Base/Acid (B/A) Ratio								
Low	<0.15	-	-	-	-	-	-	-
Medium	0.15 - 0.30	0.21	-	-	-	-	-	-
High	0.27 - 0.50	-	0.35	-	-	-	-	-
Severe	>0.50	-	-	0.97	0.98	1.40	1.45	0.62
Potential slagging temp (Tps, °C)								
Low	>1340	-	-	-	-	-	-	-
Medium	1340 - 1230	1267	-	1267	-	-	-	-
High	1230 - 1150	-	1177	-	1151	-	-	-
Severe	<1150	-	-	-	-	1163	1160	1170

Table 20 - Comparative indices of slagging potential
- superheater deposits (fine grind)

Slagging propensity	Reference limits	Original ash source - fine grind						
		Ref. coal C-1B	C-2B	C-3B	C-4B	C-5B	C-6B	C-7B
Base/Acid (B/A) Ratio								
Low	<0.15	-	-	-	-	-	-	-
Medium	0.15 - 0.30	0.21	-	-	-	-	-	-
High	0.27 - 0.50	-	0.34	-	-	-	-	-
Severe	>0.50	-	-	0.72	0.81	1.23	1.69	0.72
Potential Slagging Temp (Tps, °C)								
Low	>1340	-	-	-	-	-	-	-
Medium	1340 - 1230	1233	-	-	-	-	-	-
High	1230 - 1150	-	1180	1176	1150	1185	1180	1150
Severe	<1150	-	-	-	-	-	-	-

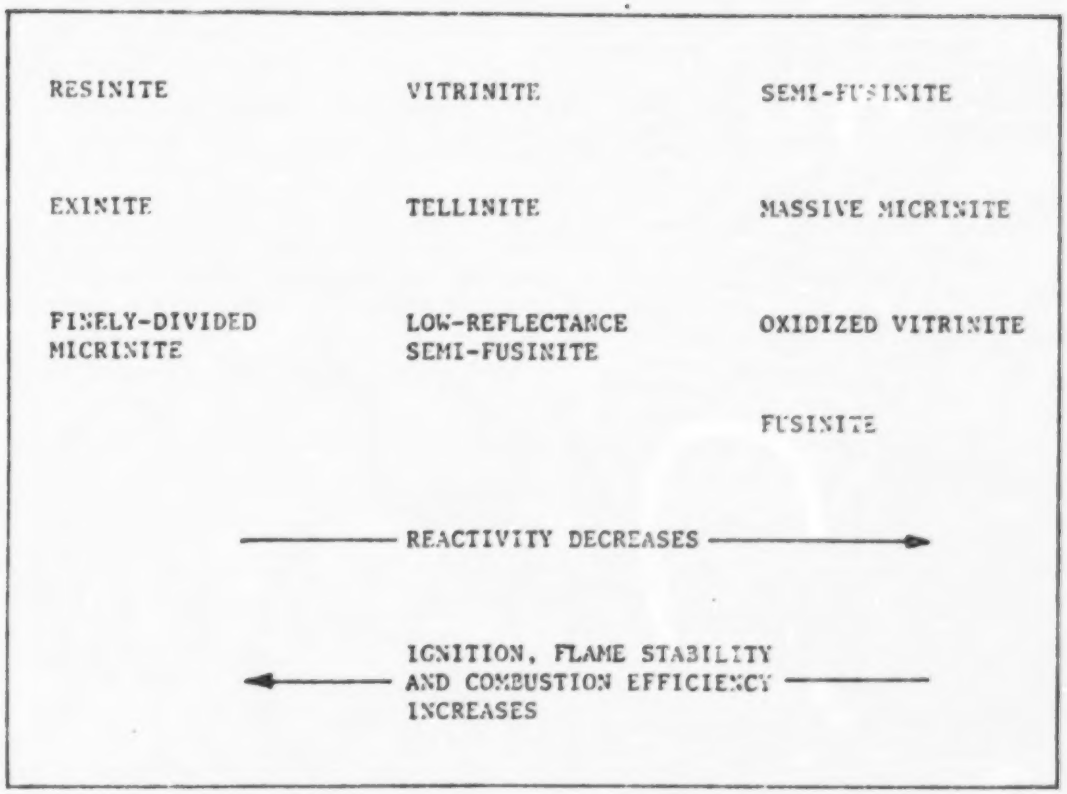


Fig. 1- Influence of coal maceral type on combustion

CLASSIFICATION OF COAL BY RANK

Canada uses the systems and procedures of the American Society for Testing and Materials (ASTM) for sampling, analysing and classifying coals by rank, as detailed in the Annual Book of ASTM Standards. Basically coals are ranked according to their degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite.

Classification in the ASTM system is a function of fixed carbon content and calorific value calculated on the mineral-matter-free basis. The high rank coals are classed according to calorific value on the moist basis. The agglomerating characteristics of coals (i.e. their binding and/or swelling qualities when heated in the absence of oxygen) are used to differentiate between certain adjacent groups in the ranking.

VM%*	FC%*	CLASS	GROUP	CALORIFIC VALUE**	
				Btu per lb	Mj/kg
2	98	Anthracite(1)	Meta Anthracite		
8	92		Anthracite		
14	86		Semianthracite		
22	78	Bituminous(2)	Low Volatile Bituminous		
31	69		Medium Volatile Bituminous		
			High Volatile A Bituminous	14 000	32.6
			High Volatile B Bituminous	13 000	30.2
			High Volatile C Bituminous		
		Sub-bituminous(4)	Sub-bituminous A(3)	11 500	26.7
			Sub-bituminous B	10 500	24.4
			Sub-bituminous C	9 500	22.1
		Lignitic(4)	Lignite A	8 300	19.3
			Lignite B	6 300	14.7

* Dry, mineral-matter-free basis
**Moist, mineral-matter-free basis
(1) Non-agglomerating; if agglomerating classified as low volatile bituminous
(2) Commonly agglomerating
(3) If agglomerating classified as high volatile C bituminous
(4) Non agglomerating
VM Volatile matter
FC Fixed carbon

Source: Energy, Mines and Resources, Canada CANMET Report 83-20E

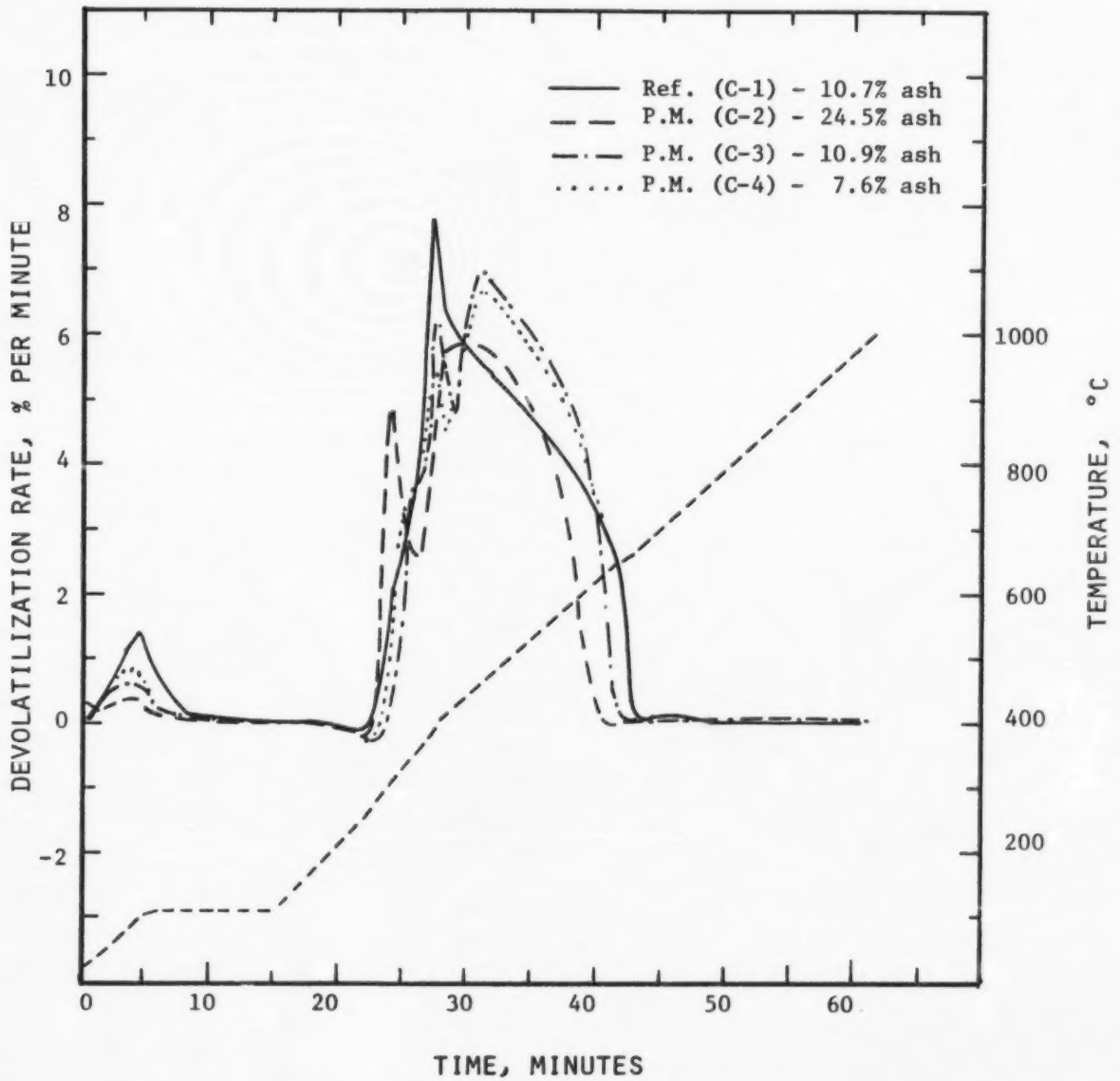


Fig. 3a - Comparative thermogravimetric analysis of Prince Mine coals and a thermal reference coal

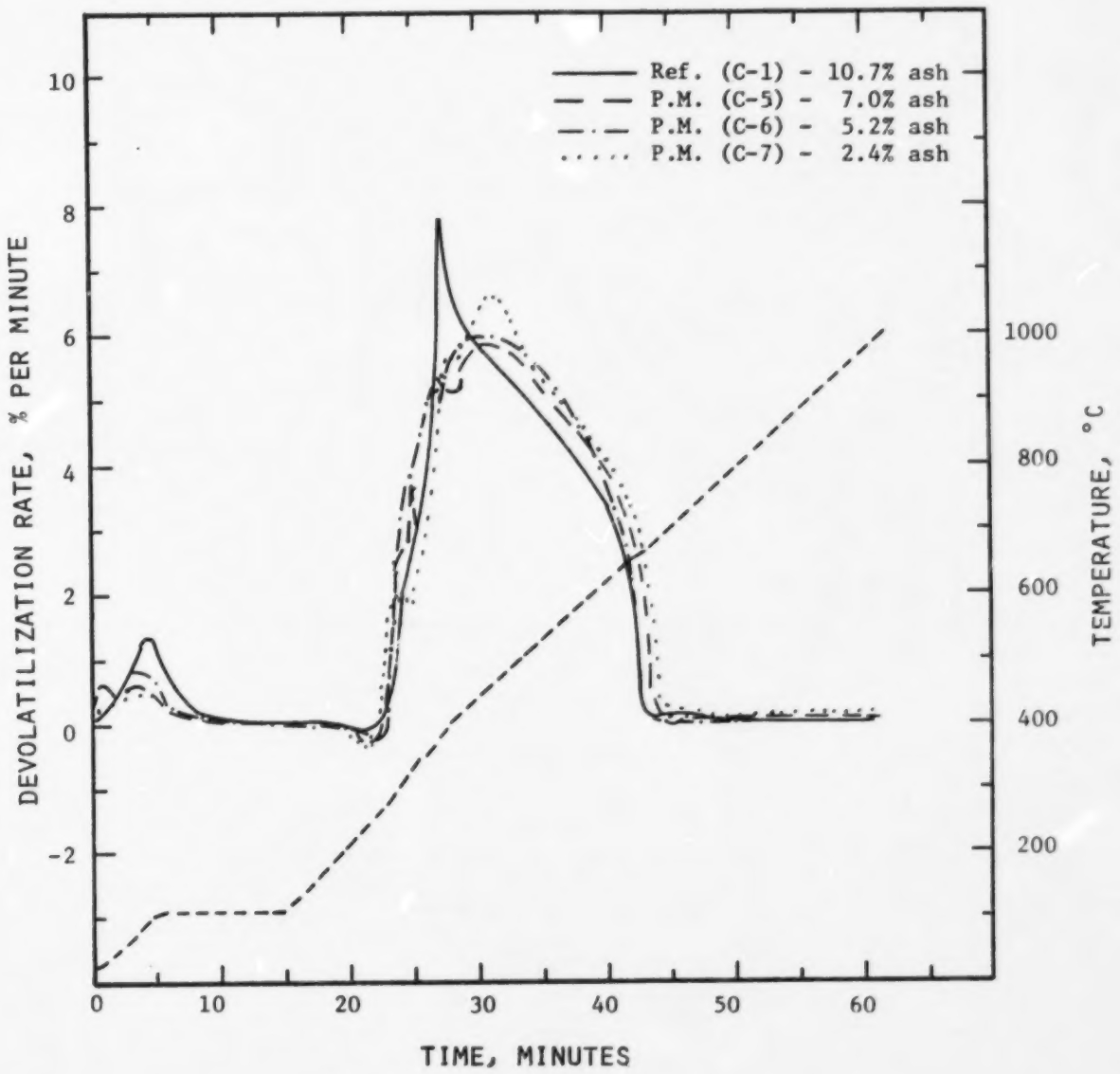


Fig. 3b - Comparative thermogravimetric analysis of Prince Mine coals and a thermal reference coal

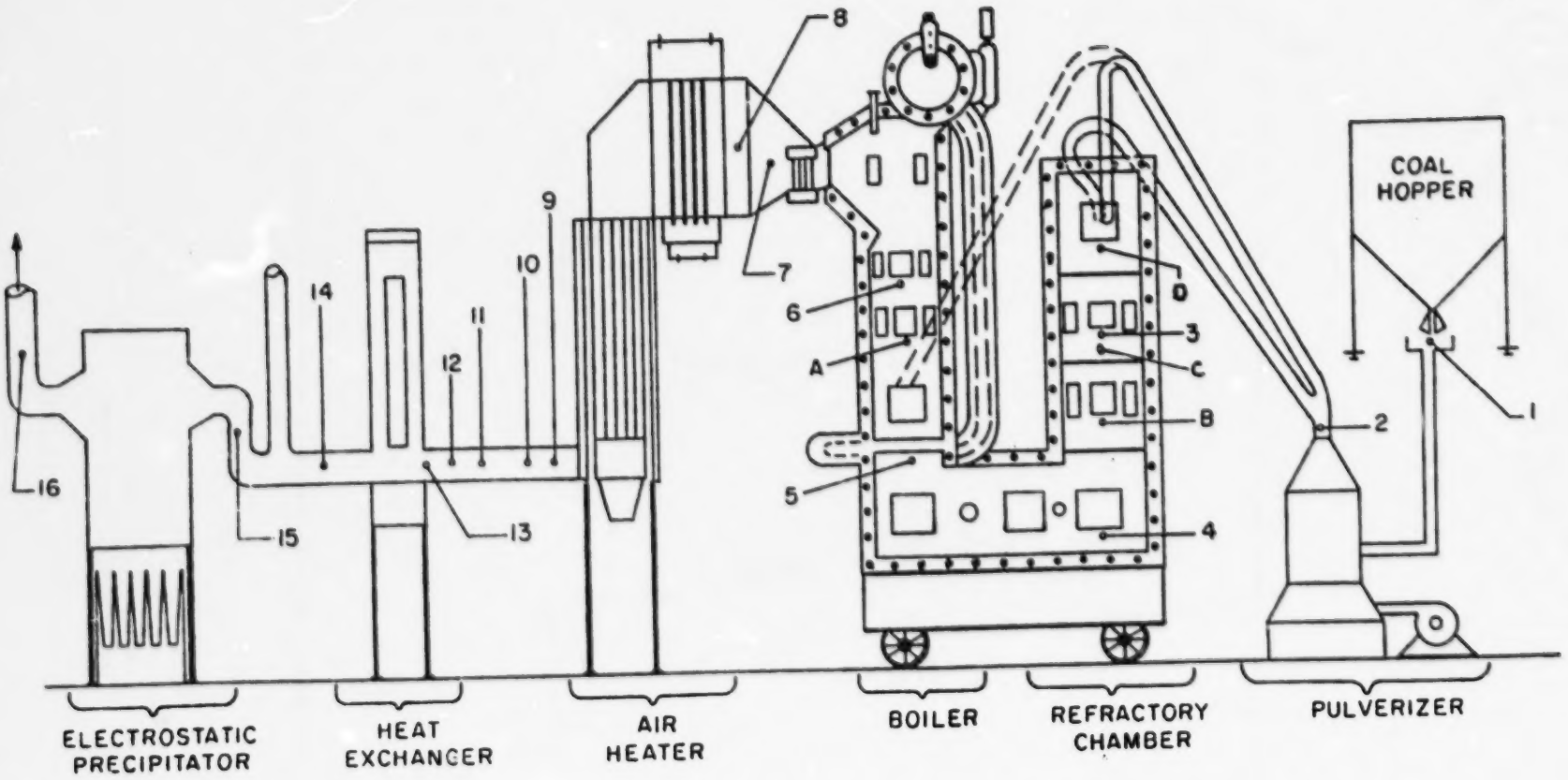


Fig. 4 - Schematic illustration of the pilot-scale boiler - showing sampling stations

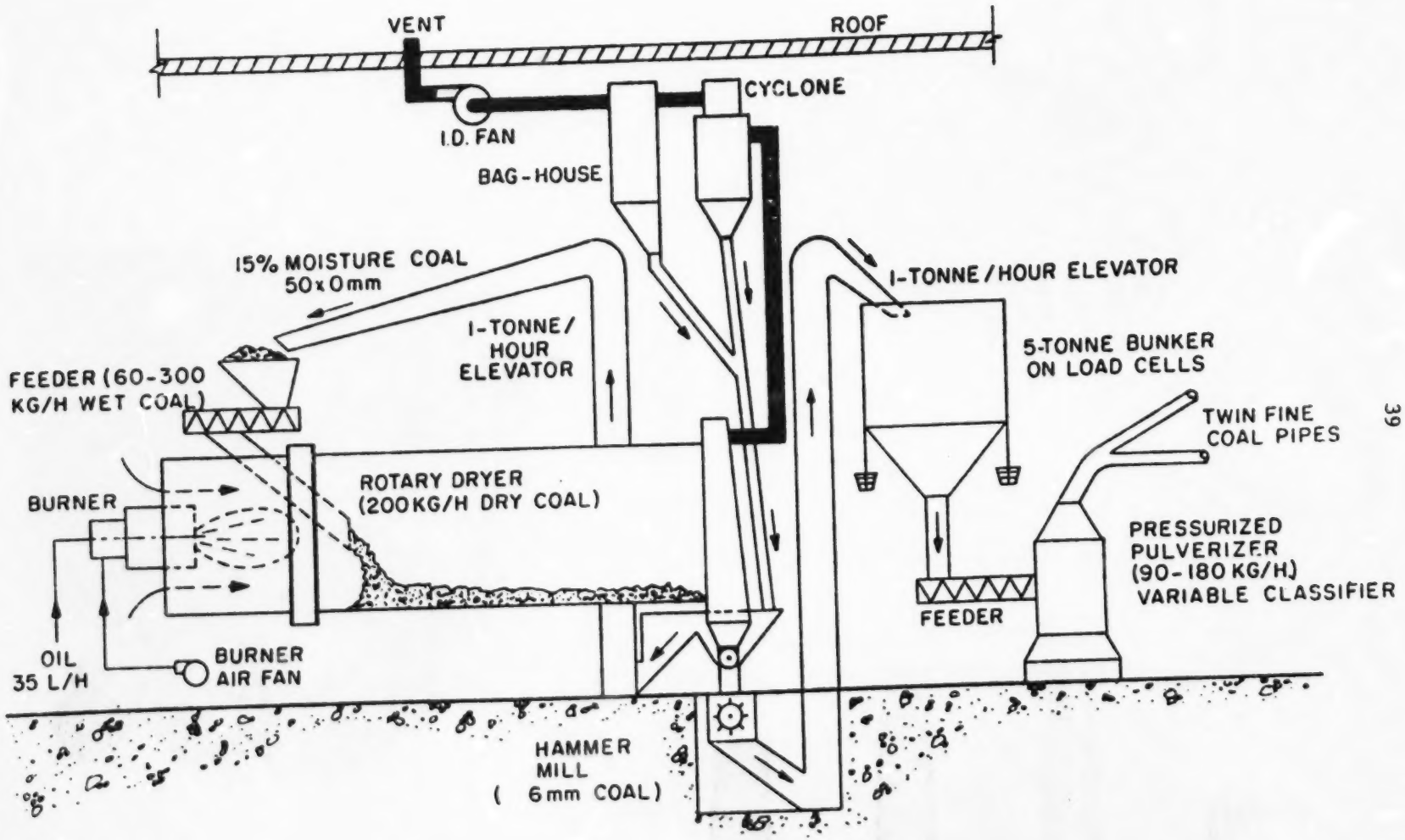
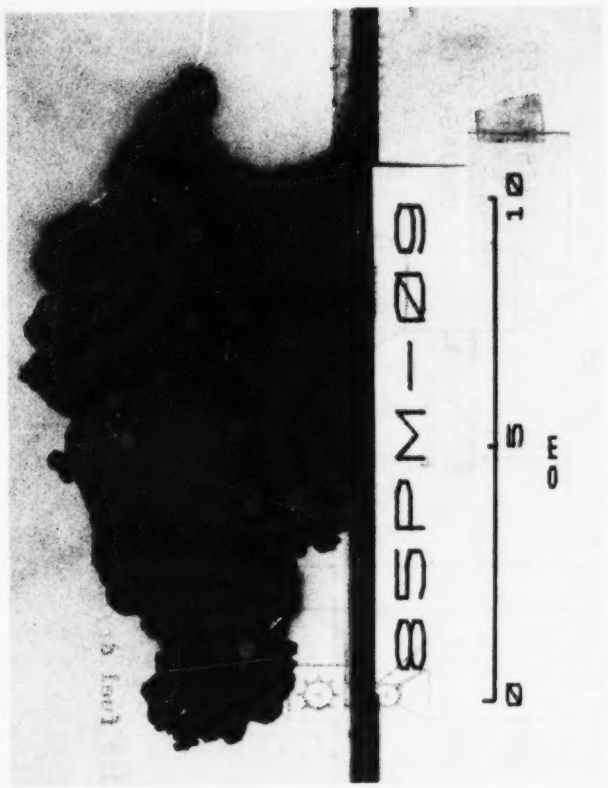
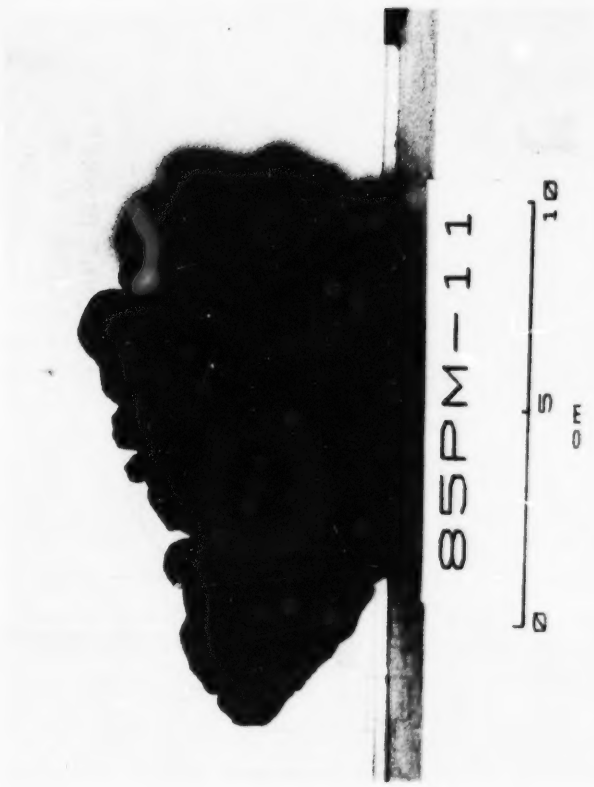


Fig. 5 - Schematic illustration of solid fuel drying and grinding system



Raw Coal (C-2)



Deep Cleaned Coal (C-7)

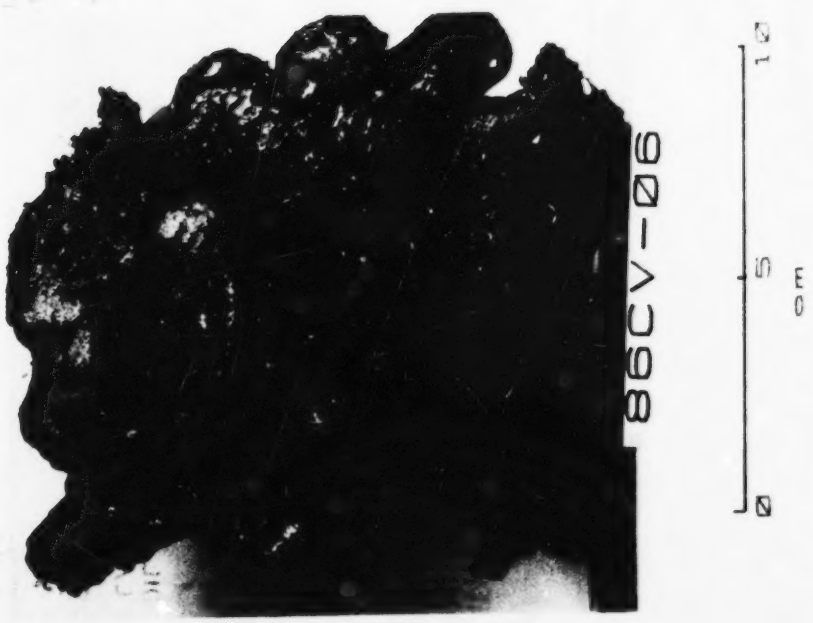


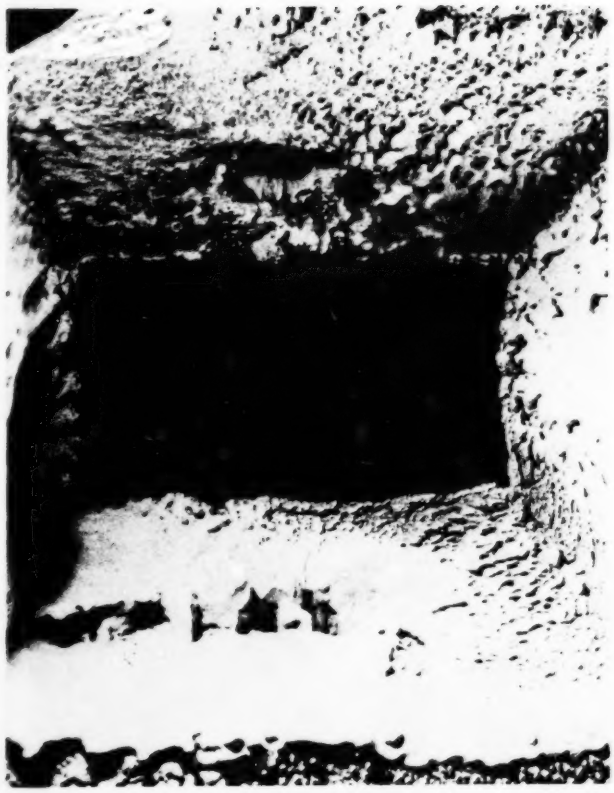
Fig. 6 - Cross-sectional Photographs of Furnace Bottom Deposits

Raw Coal (C-2)

Deep Cleaned Coal (C-7)

Reference Coal (C-1)

Fig. 7 - Deposits in Furnace Bottom



Raw Coal (C-2)

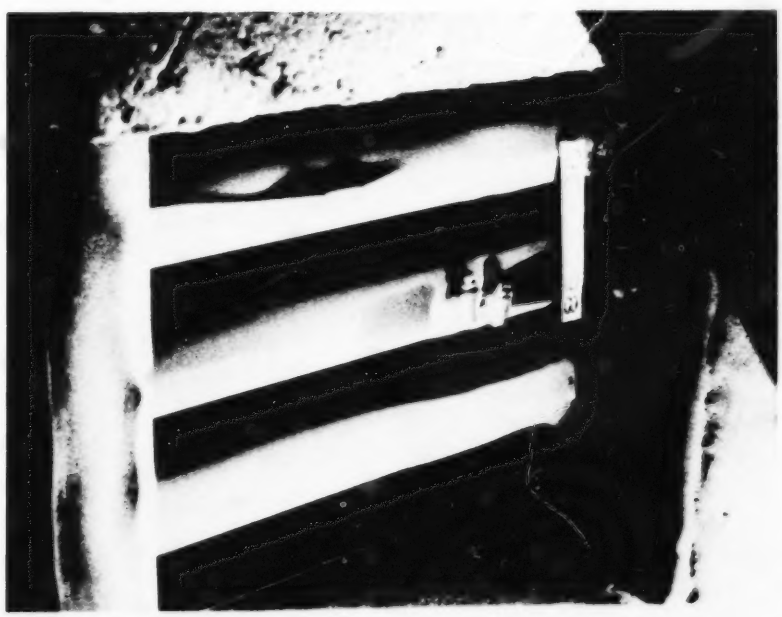
Deep Cleaned Coal (C-7)

Reference Coal (C-1)

Fig. 8 - Deposits on Refractory and Water-Walls of Furnace

Raw Coal (C-2)

Deep Cleaned Coal (C-7)



Reference Coal (C-1)

Fig. 9 - Deposits on Superheater Tubes

APPENDIX "A"

COMBUSTION CHARTS

FOR

PRINCE MINE

RAW COAL

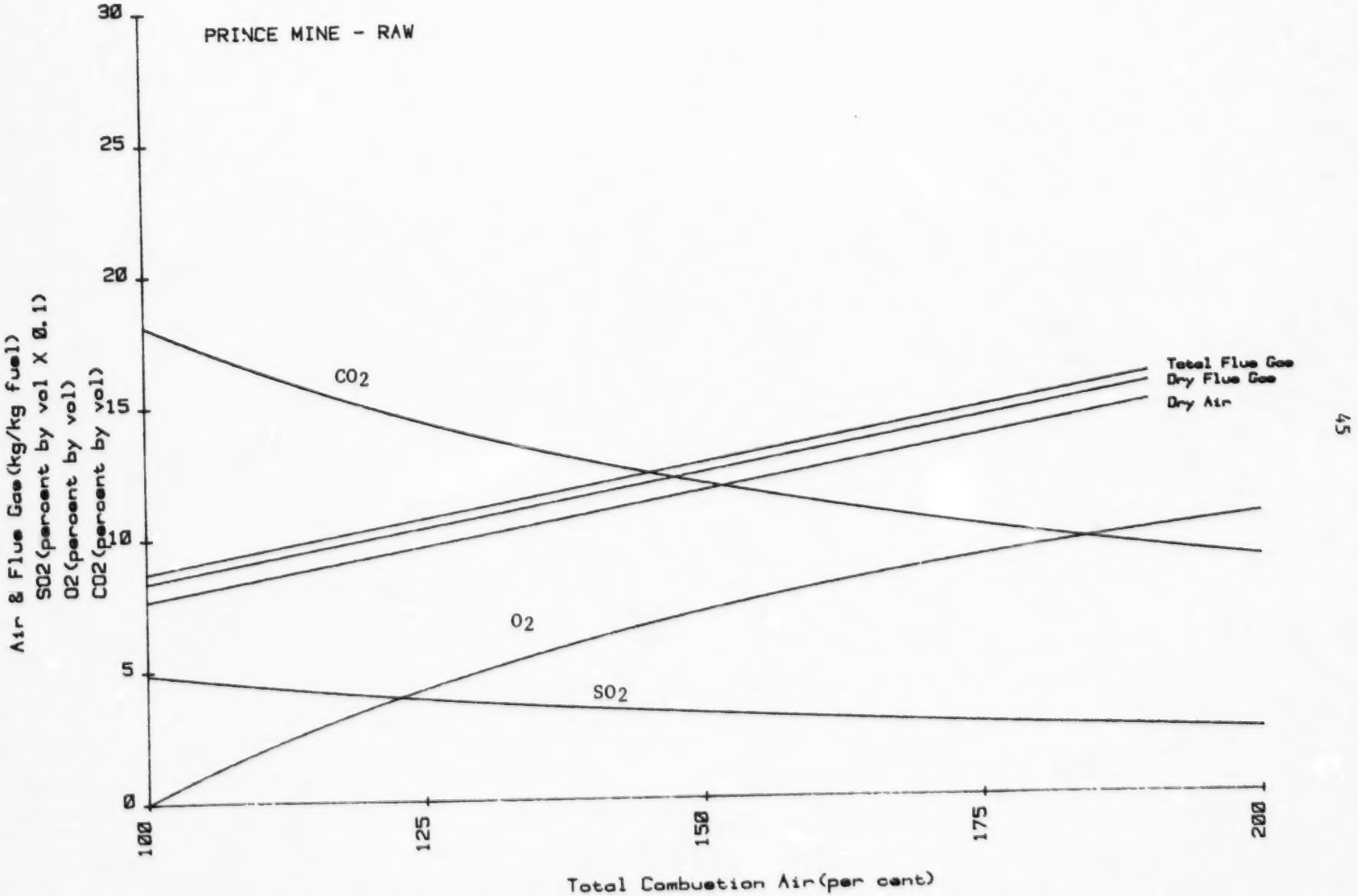


Fig. 1A - Combustion data, weight basis

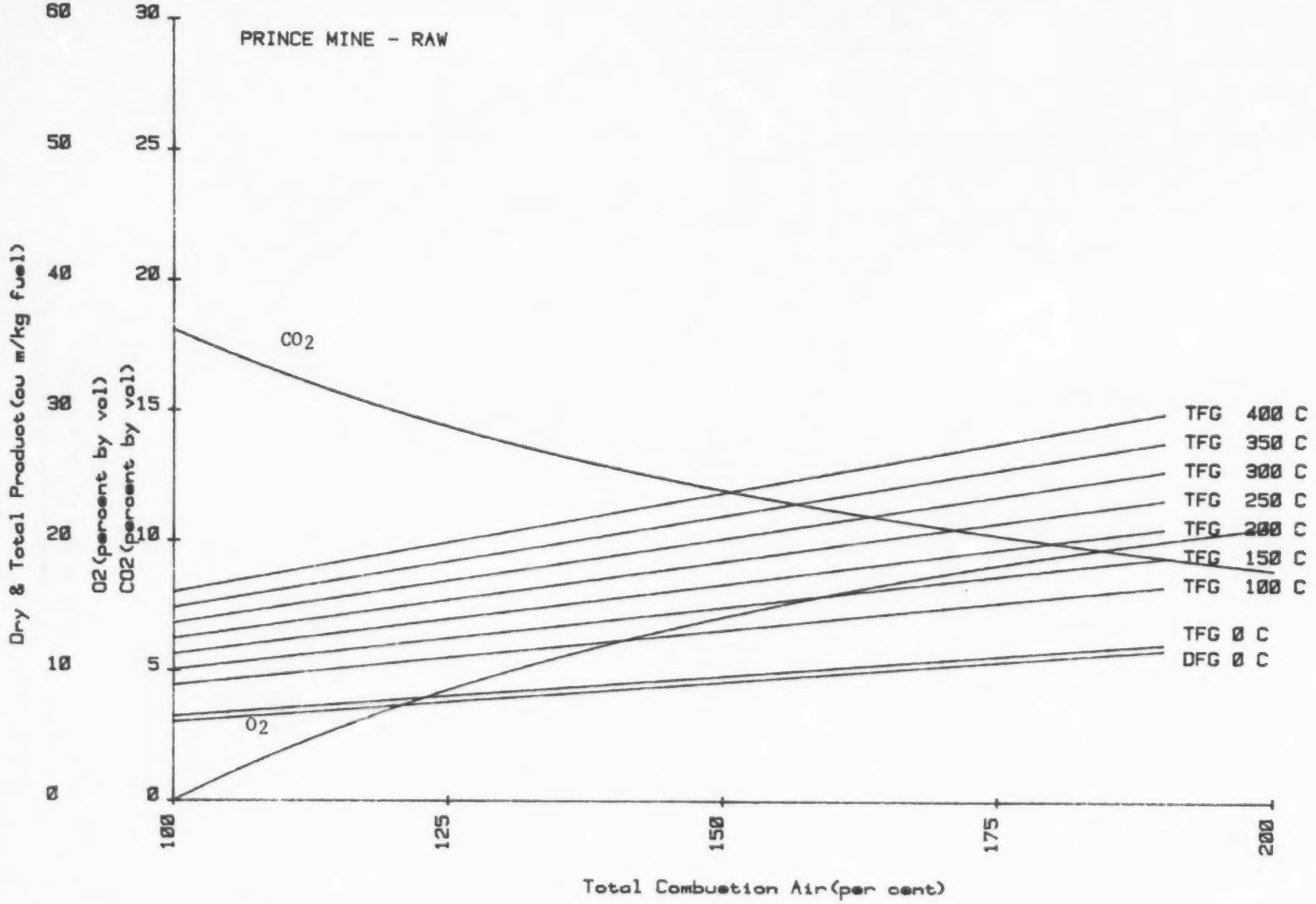


Fig. 2A - Combustion data, volume basis

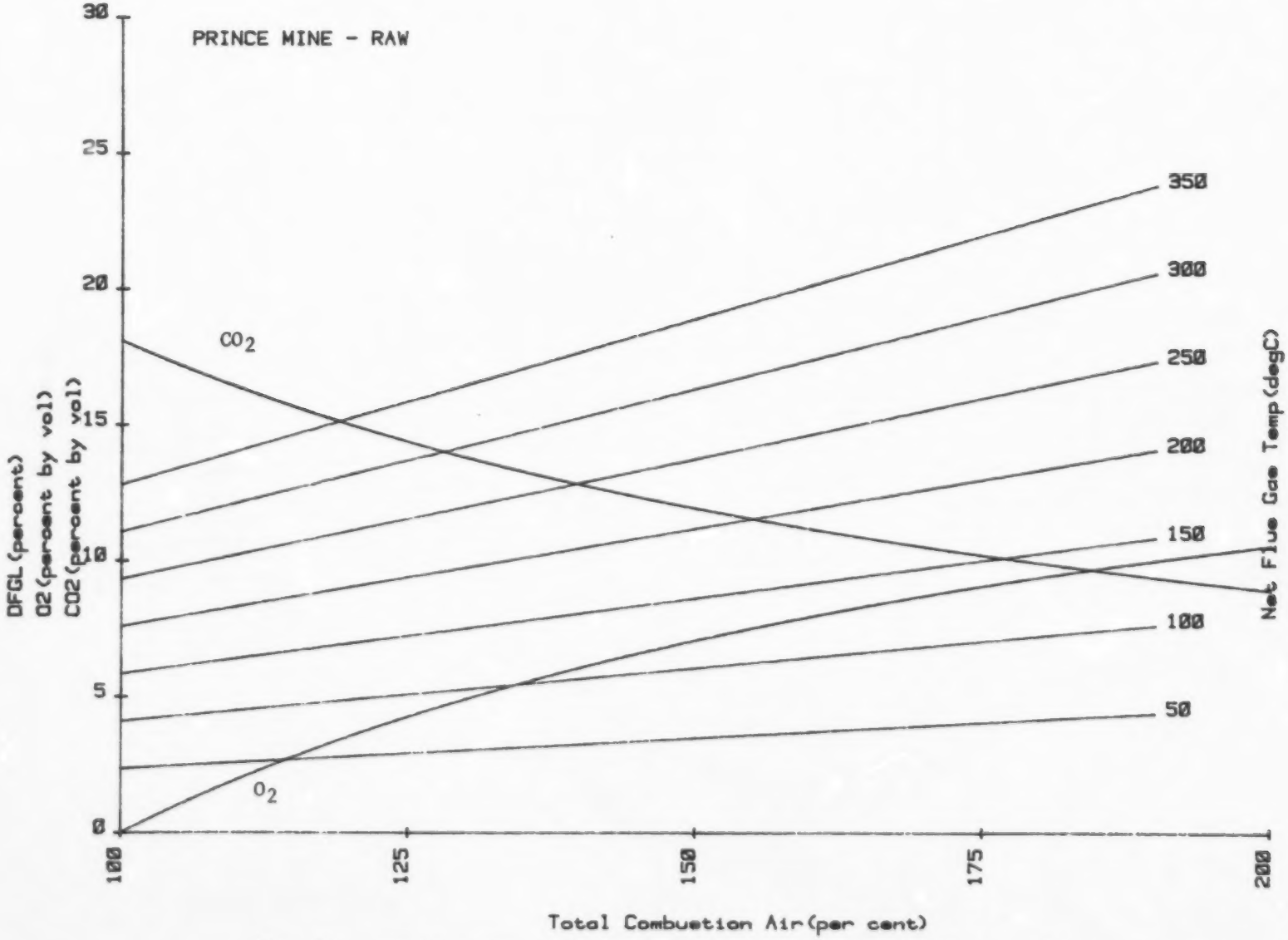


Fig. 3A - Dry flue gas loss for a range of temperature differentials

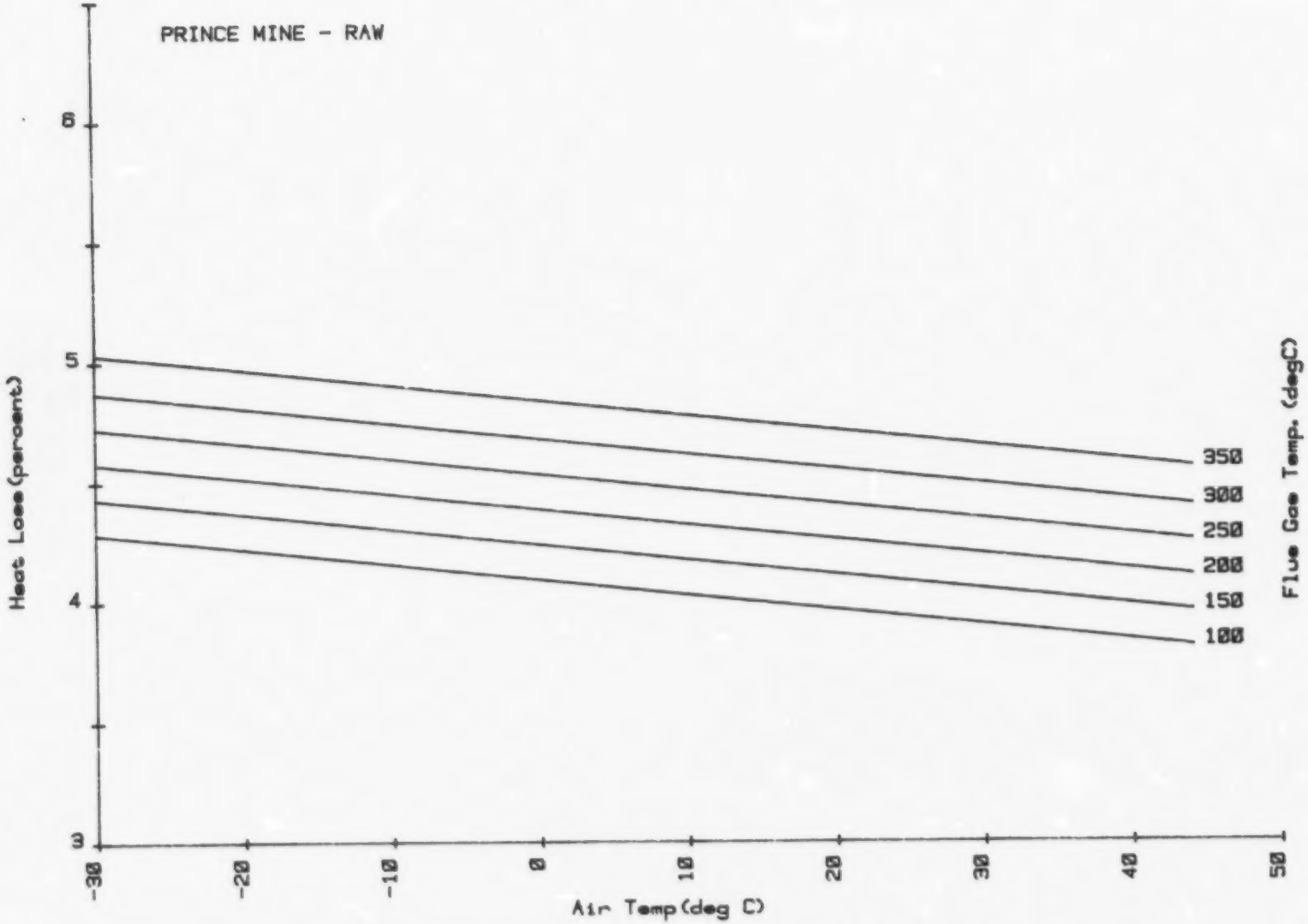


Fig. 4A - Hydrogen loss for a range of stack temperatures

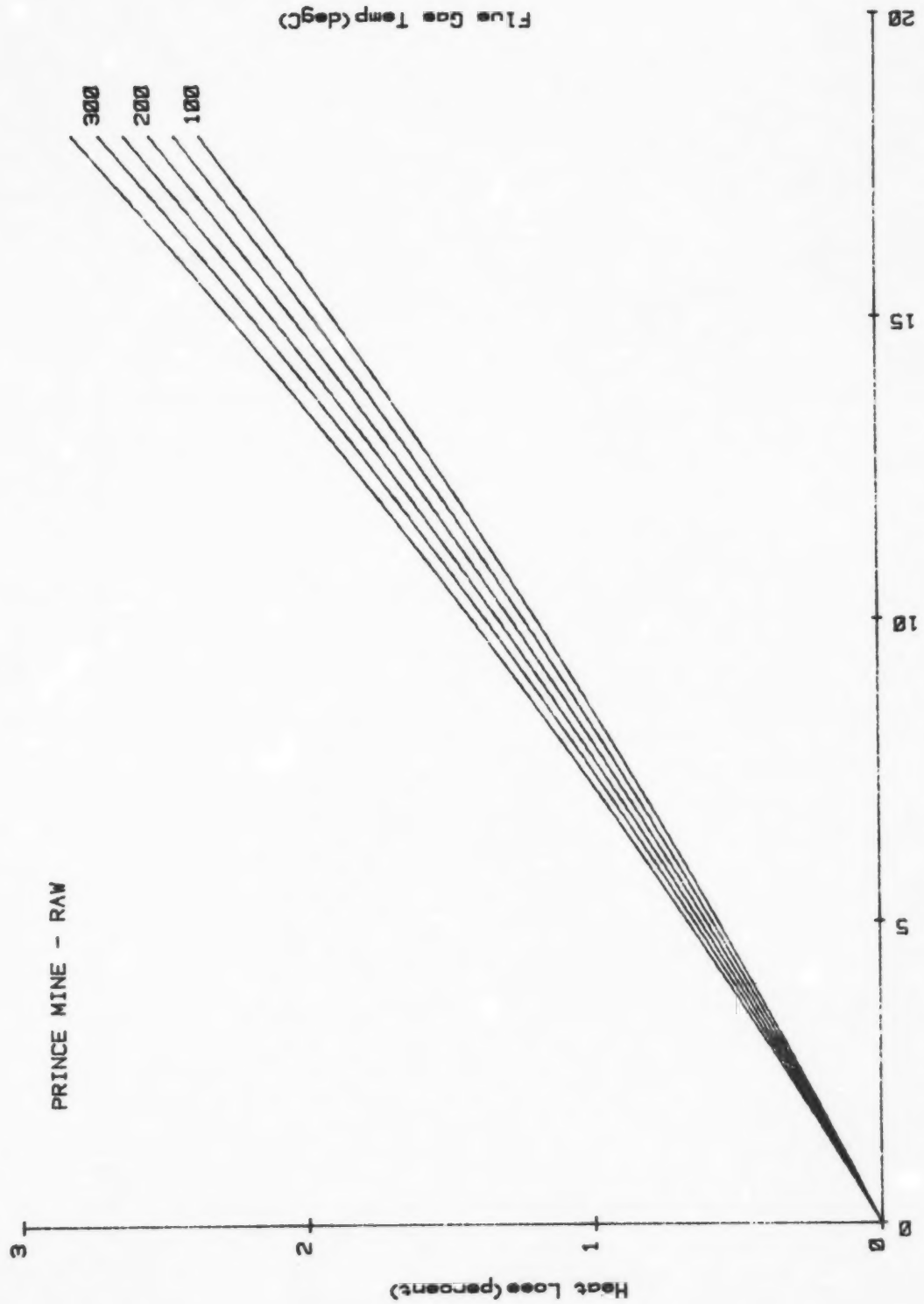


Fig. 5A - Heat loss due to moisture in coal

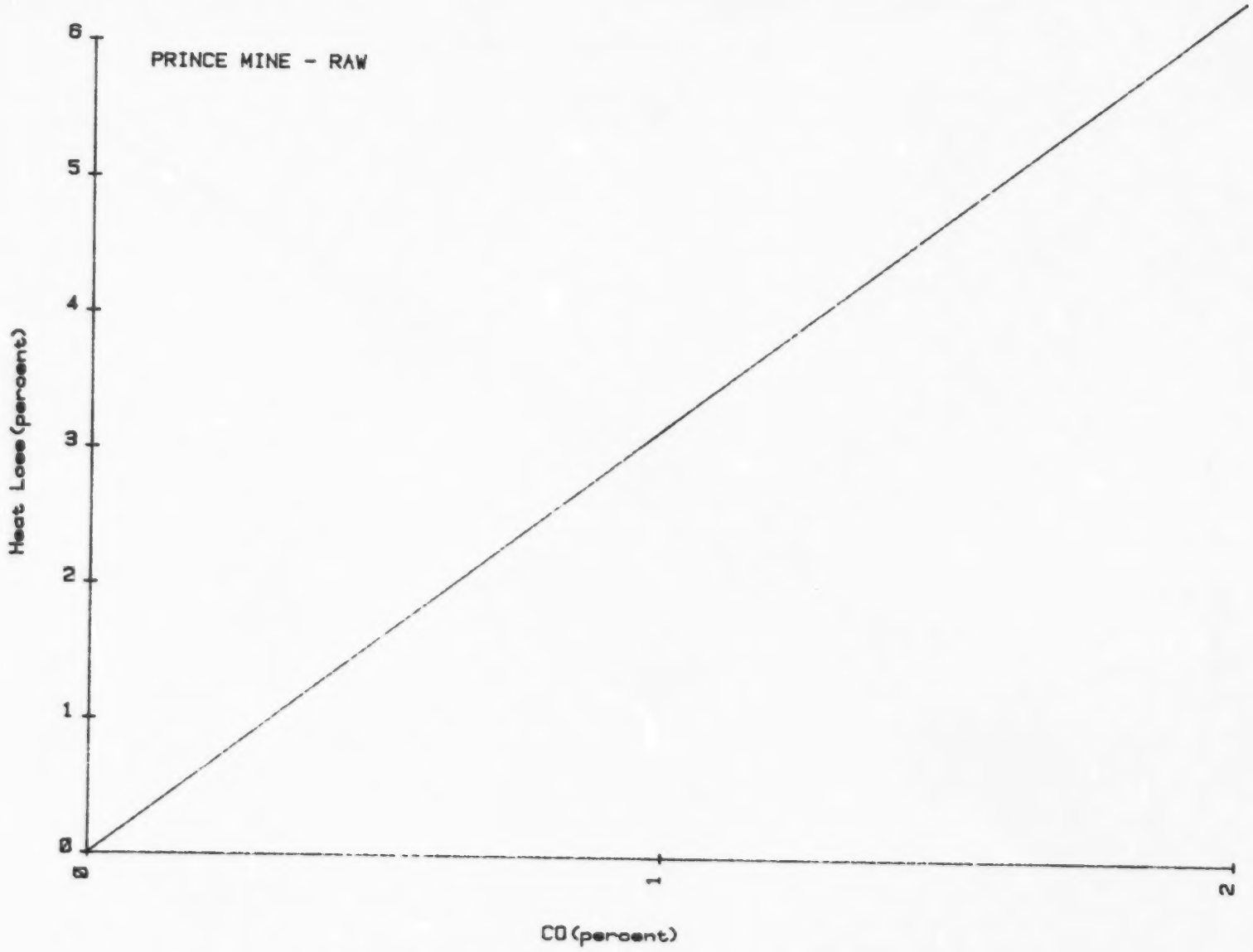


Fig. 6A - Heat loss for a range of CO concentrations
(assuming negligible excess air)